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# Coloron phenomenology

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## Abstract

A flavor-universal extension of the strong interactions was recently proposed in response to the apparent excess of high- $E_T$  jets in the inclusive jet spectrum measured at the Tevatron. This paper studies the color octet of massive gauge bosons ('colorons') that is present in the low-energy spectrum of the model's Higgs phase. Constraints from searches for new particles decaying to dijets and from measurements of the weak-interaction  $\rho$  parameter imply that the colorons must have masses greater than 870-1000 GeV. The implications of recent Tevatron data and the prospective input from future experiments are also discussed.

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A flavor-universal coloron model [1] was recently proposed to explain the apparent excess of high- $E_T$  jets in the inclusive jet spectrum measured by CDF [2]. This model is a flavor-universal variant of the coloron model of Hill and Parke [3] which can accommodate the jet excess without contradicting other experimental data. It involves a minimal extension of the standard description of the strong interactions, including the addition of one gauge interaction and a scalar multiplet, but no new fermions. Furthermore, the flavor-universal coloron model of the strong interactions can be grafted onto the standard one-Higgs-doublet model of electroweak physics, yielding a simple, complete, and renormalizable theory.

The model serves as a useful baseline with which to compare both the data and other candidate explanations of the jet excess. The latter include such diverse physics as modified parton distribution functions [4], higher-order contributions from gluon resummation [5], phenomenological models of quark substructure [2], new strongly-coupled  $Z'$  gauge bosons [6], quark resonances [7], non-standard triple-gauge vertices [8], and light gluinos [9].

This letter explores the phenomenology of the Higgs phase of the model, in which an octet of strongly-interacting massive gauge bosons (colorons) is present in the low-energy spectrum. Previous work on this model has considered effects on the inclusive jet spectrum [1] and the dijet spectrum and angular distributions [10] in the approximation where coloron exchange is treated as a four-fermion contact interaction. The four-fermion approximation is appropriate for heavy colorons and conveniently allows the model's effects to be represented in terms of a single parameter: the coefficient of the contact interaction. The present work goes beyond the four-fermion approximation by including propagating colorons of finite width. This allows us to investigate the phenomenology of colorons too light to be well-described by contact interactions at Tevatron energies. It also enables us to explore the separate dimensions of the coloron parameter space (mass and mixing angle) independently.

We begin by reviewing the main features of the model, in both the Higgs and confining phases. Then, focusing on the Higgs phase, we discuss the effect that the presence of colorons strongly coupled to quarks will have on partonic scattering cross-sections. In section 3, we show what limits may already be placed on the mass and mixing angle of the colorons. Next, we discuss how further experiments can probe the model at higher coloron masses. Our conclusions appear in section 5.

## 1 The model

In the flavor-universal coloron model [1], the strong gauge group is extended to  $SU(3)_1 \times SU(3)_2$ . The gauge couplings are, respectively,  $\xi_1$  and  $\xi_2$  with  $\xi_1 \ll \xi_2$ .

Each quark transforms as a (1,3) under this extended strong gauge group.

The model also includes a scalar boson  $\Phi$  transforming as a  $(3, \bar{3})$  under the two  $SU(3)$  groups. The most general<sup>1</sup> potential for  $\Phi$  is

$$U(\Phi) = \lambda_1 \text{Tr} \left( \Phi \Phi^\dagger - f^2 \mathbf{I} \right)^2 + \lambda_2 \text{Tr} \left( \Phi \Phi^\dagger - \frac{1}{3} \mathbf{I} (\text{Tr} \Phi \Phi^\dagger) \right)^2 \quad (1.1)$$

where the overall constant has been adjusted so that the minimum of  $U$  is zero. For  $\lambda_1, \lambda_2, f^2 > 0$  the scalar develops a vacuum expectation value  $\langle \Phi \rangle = \text{diag}(f, f, f)$  which breaks the two strong groups to their diagonal subgroup. We identify this unbroken subgroup with QCD.

The original gauge bosons mix to form an octet of massless gluons and an octet of massive colorons. The gluons interact with quarks through a conventional QCD coupling with strength  $g_3$ . The colorons ( $C^{\mu a}$ ) interact with quarks through a new QCD-like coupling

$$\mathcal{L} = -g_3 \cot \theta J_\mu^a C^{\mu a} \quad , \quad (1.2)$$

where  $J_\mu^a$  is the color current

$$\sum_f \bar{q}_f \gamma_\mu \frac{\lambda^a}{2} q_f \quad . \quad (1.3)$$

and  $\cot \theta = \xi_2 / \xi_1$ . Note that we expect  $\cot \theta > 1$ . In terms of the QCD coupling, the gauge boson mixing angle and the scalar vacuum expectation value, the mass of the colorons is

$$M_c = \left( \frac{g_3}{\sin \theta \cos \theta} \right) f \quad . \quad (1.4)$$

The colorons decay to all sufficiently light quarks; assuming there are  $n$  flavors lighter than  $M_c/2$ , the decay width is

$$\Gamma_c \approx \frac{n}{6} \alpha_s \cot^2 \theta M_c \quad (1.5)$$

where  $\alpha_s \equiv g_3^2/4\pi$ . We take the top quark mass to be 175 GeV so that  $n = 5$  for  $M_c \lesssim 350$  GeV and  $n = 6$  otherwise.

Thus far, we have described the Higgs phase of the model, in which  $SU(3)_1 \times SU(3)_2$  breaks at an energy scale where neither gauge coupling is strong. If the  $SU(3)_2$  gauge coupling becomes strong while the gauge symmetry is intact, the model enters a confining phase instead. As discussed in [1], if the strong coupling

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<sup>1</sup>As noted in [1] this model can be grafted onto the standard one-doublet Higgs model. In this case, the most general renormalizable potential for  $\Phi$  and the Higgs doublet  $\phi$  also includes the term  $\lambda_3 \phi^\dagger \phi \text{Tr}(\Phi^\dagger \Phi)$ . For a range of  $\lambda$ 's and parameters in the Higgs potential, the vacuum will break the two  $SU(3)$  groups to QCD and also break the electroweak symmetry as required.

does not break the chiral symmetries of the quarks, then it will bind the quarks and the scalar  $\Phi$  into  $SU(3)_2$ -neutral states. These composite fermionic states would correspond to the ‘ordinary quarks’ seen at low energies. The remainder of this paper will concentrate on the phenomenology of the Higgs phase of the model; for more on the confining phase’s phenomenology see ref. [1].

## 2 Partonic cross-sections involving colorons

Production and exchange of the massive colorons will affect hadronic cross-sections. To quantify this observation, we need to calculate the effect of the colorons on each partonic scattering sub-process. Two-body scattering involving external gluons remains the same as in QCD; the relevant cross-sections may be found in [11]. Processes involving external quarks are modified by coloron exchange and the cross-sections are given below.

For each two-body parton scattering cross-section, we write

$$\frac{d\sigma}{d\hat{t}}(ab \rightarrow cd) = \frac{\pi\alpha_s^2}{\hat{s}^2}\Sigma(ab \rightarrow cd) \quad (2.1)$$

to define the  $\Sigma(ab \rightarrow cd)$ , which conventionally include initial state color averaging factors and are written in terms of the partonic Mandelstam invariants  $\hat{s}$ ,  $\hat{t}$ , and  $\hat{u}$ . For scattering of light quarks, whose masses may be neglected, we have

$$\Sigma(qq' \rightarrow qq') = \frac{4}{9}(\hat{s}^2 + \hat{u}^2) \left[ \frac{1}{\hat{t}^2} + \frac{2 \cot^2 \theta (\hat{t} - M_c^2)}{\hat{t} |\hat{t}_c|^2} + \frac{\cot^4 \theta}{|\hat{t}_c|^2} \right] \quad (2.2)$$

$$\Sigma(q\bar{q} \rightarrow q'\bar{q}') = \frac{4}{9}(\hat{t}^2 + \hat{u}^2) \left[ \frac{1}{\hat{s}^2} + \frac{2 \cot^2 \theta (\hat{s} - M_c^2)}{\hat{s} |\hat{s}_c|^2} + \frac{\cot^4 \theta}{|\hat{s}_c|^2} \right] \quad (2.3)$$

$$\begin{aligned} \Sigma(qq \rightarrow qq) &= \frac{4}{9}(\hat{s}^2 + \hat{u}^2) \left[ \frac{1}{\hat{t}^2} + \frac{2 \cot^2 \theta (\hat{t} - M_c^2)}{\hat{t} |\hat{t}_c|^2} + \frac{\cot^4 \theta}{|\hat{t}_c|^2} \right] \\ &+ \frac{4}{9}(\hat{s}^2 + \hat{t}^2) \left[ \frac{1}{\hat{u}^2} + \frac{2 \cot^2 \theta (\hat{u} - M_c^2)}{\hat{u} |\hat{u}_c|^2} + \frac{\cot^4 \theta}{|\hat{u}_c|^2} \right] \\ &- \frac{8}{27}\hat{s}^2 \left[ \frac{1}{\hat{t}\hat{u}} + \frac{\cot^2 \theta (\hat{t} - M_c^2)}{\hat{u} |\hat{t}_c|^2} + \frac{\cot^2 \theta (\hat{u} - M_c^2)}{\hat{t} |\hat{u}_c|^2} \right. \\ &\quad \left. + \frac{\cot^4 \theta [(\hat{t} - M_c^2)(\hat{u} - M_c^2) + \Gamma^2(s)M_c^2]}{|\hat{t}_c|^2 |\hat{u}_c|^2} \right] \end{aligned} \quad (2.4)$$

$$\begin{aligned}
\Sigma(q\bar{q} \rightarrow q\bar{q}) &= \frac{4}{9}(\hat{s}^2 + \hat{u}^2) \left[ \frac{1}{\hat{t}^2} + \frac{2 \cot^2 \theta (\hat{t} - M_c^2)}{\hat{t} |\hat{t}_c|^2} + \frac{\cot^4 \theta}{|\hat{t}_c|^2} \right] \\
&+ \frac{4}{9}(\hat{t}^2 + \hat{u}^2) \left[ \frac{1}{\hat{s}^2} + \frac{2 \cot^2 \theta (\hat{s} - M_c^2)}{\hat{s} |\hat{s}_c|^2} + \frac{\cot^4 \theta}{|\hat{s}_c|^2} \right] \\
&- \frac{8}{27}\hat{u}^2 \left[ \frac{1}{\hat{s}\hat{t}} + \frac{\cot^2 \theta (\hat{s} - M_c^2)}{\hat{t} |\hat{s}_c|^2} + \frac{\cot^2 \theta (\hat{t} - M_c^2)}{\hat{s} |\hat{t}_c|^2} \right. \\
&\quad \left. + \frac{\cot^4 \theta [(\hat{s} - M_c^2)(\hat{t} - M_c^2) + \Gamma^2(s)M_c^2]}{|\hat{s}_c|^2 |\hat{t}_c|^2} \right]
\end{aligned} \tag{2.5}$$

where  $q'$  denotes a quark of a flavor other than  $q$ , and where  $\hat{s}_c \equiv \hat{s} - M_c^2 + i\Gamma(s)M_c$  and similar definitions hold for  $\hat{t}_c$  and  $\hat{u}_c$ . In the above expressions,  $\Gamma(s)$  is the  $s$ -dependent width of the coloron

$$\begin{aligned}
\Gamma(s) &\approx \frac{n}{6} \cot^2 \theta \sqrt{\hat{s}} \quad \hat{s} < M_c^2 \\
&= \Gamma_c \quad \hat{s} > M_c^2
\end{aligned} \tag{2.6}$$

The top quark is heavy enough to warrant separate treatment. The proton's top quark content is negligible and we need not consider processes involving initial-state top quarks. Furthermore, top quarks are produced in quark-quark scattering with a mass-dependent cross-section [12]; when the contributions of colorons are included, we find

$$\begin{aligned}
\Sigma(q\bar{q} \rightarrow t\bar{t}) &= \frac{4}{9}(\hat{t}^2 + \hat{u}^2 + 4m_t^2\hat{s} - 2m_t^4) \times \\
&\quad \left[ \frac{1}{\hat{s}^2} + \frac{2 \cot^2 \theta (\hat{s} - M_c^2)}{\hat{s} |\hat{s}_c|^2} + \frac{\cot^4 \theta}{|\hat{s}_c|^2} \right].
\end{aligned} \tag{2.7}$$

The cross-section for  $gg \rightarrow t\bar{t}$  is the same as in QCD and may be found in ref. [12].

### 3 Existing limits on colorons

We now describe the limits that may already be placed on the mass and mixing angle of the colorons. Scattering data from hadron colliders and measurements of the weak-interaction  $\rho$  parameter provide experimental input. The condition that the model be in the Higgs phase imposes a further bound on the mixing angle.

#### 3.1 dijets

A sufficiently light coloron would be visible in direct production at the Tevatron. Indeed, the CDF Collaboration has searched for new particles decaying to dijets and

reported [13] an upper limit on the incoherent production of such states. Accordingly, we calculated  $\sigma \cdot B$  for colorons with various values of  $M_c$  and  $\cot \theta$ ; the results for  $\cot \theta = 1, 1.5$  are shown in figure 1 together with the CDF limit. In calculating  $\sigma \cdot B$ , we followed the example of CDF in using CTEQ structure functions and in requiring  $|\eta| < 2$  and  $|\cos \theta^*| < 2/3$ . For  $\cot^2 \theta < 2$ , the coloron's half-width falls within the dijet mass resolution of 10%; for larger  $\cot \theta$  we counted only the portion of the signal that falls within a bin centered on the coloron mass and with a width equal to the resolution.

Values of  $M_c$  and  $\cot \theta$  which yield a theoretical prediction that exceeds the CDF upper limit are deemed to be excluded at 95% c.l. [13]. We find that for  $\cot \theta = 1$ , the range  $200\text{GeV} < M_c < 870\text{GeV}$  is excluded; at  $\cot \theta = 1.5$ , the upper limit of the excluded region rises to roughly 950 GeV; at  $\cot \theta = 2$ , it rises to roughly 1 TeV. As the coloron width grows like  $\cot^2 \theta$ , going to higher values of  $\cot \theta$  does not appreciably increase the upper limit of the excluded range of masses beyond 1 TeV.

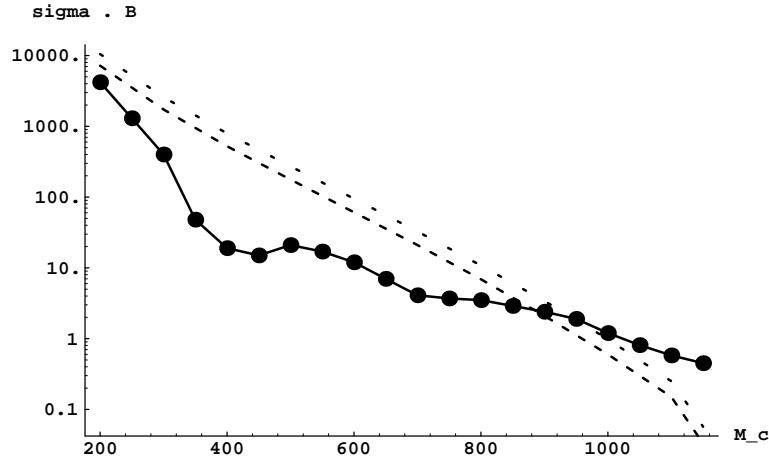


Figure 1: Experimental [13] upper limit on the cross-section times branching ratio for new particles decaying to dijets (points) is compared to theoretical predictions for colorons with  $\cot \theta = 1$  (lower dashed curve) and  $\cot \theta = 1.5$  (upper dashed curve). Both jets are required to have pseudorapidity  $|\eta| < 2.0$  and the dijet satisfies  $|\cos \theta^*| < 2/3$ . The experimental curve is based on  $19\text{pb}^{-1}$  of data.

We can extend the excluded range of coloron masses to values below those probed by CDF by noting two things. First,  $\sigma$  increases as  $\cot \theta$  does, so that exclusion of  $\cot \theta = 1$  for a given  $M_c$  implies exclusion of all higher values of  $\cot \theta$  at that  $M_c$ .

Second,  $\sigma \cdot B$  is the same for a coloron with  $\cot \theta = 1$  as for an axigluon<sup>2</sup> of identical mass<sup>3</sup>, as one may verify by comparing our equations (1.5) and (2.3) with equations (1.1) and (2.2) in ref. [15]. Axigluons with masses between 150 and 310 GeV have already been excluded by UA1's analysis [16] of incoherent axigluon production; by extension, colorons in this mass range with  $\cot \theta \geq 1$  are also excluded.

The combined excluded ranges of  $M_c$  are

$$\begin{aligned} 150\text{GeV} < M_c < 870\text{GeV} & \quad \cot \theta = 1 \\ 150\text{GeV} < M_c < 950\text{GeV} & \quad \cot \theta = 1.5 \\ 150\text{GeV} < M_c < 1000\text{GeV} & \quad \cot \theta \gtrsim 2 \end{aligned} \quad (3.1)$$

They are summarized by the shaded region of figure 2

### 3.2 b-tagged dijets

Because the colorons couple to all flavors of quarks, they should also affect the sample of b-tagged dijets observed at Tevatron experiments. The CDF Collaboration has reported [17] limits on certain new particles decaying to b-tagged dijets, based on the 1992-3 run. Their limit on narrow topgluons indicates the kind of limit that the data would provide for colorons.

Briefly, topgluons [3] belong to an  $SU(3)_1 \times SU(3)_2$  model in which light quarks transform as (3,1)'s while  $t$  and  $b$  are (1,3)'s. When the  $SU(3)_1 \times SU(3)_2$  breaks to its diagonal QCD subgroup, an octet of gauge bosons becomes massive. These topgluons,  $B^{\mu a}$ , couple to quarks as [3]

$$\mathcal{L} = - \left[ g_3 \cot \theta_t \left( \bar{t} \gamma_\mu \frac{\lambda_A}{2} t + \bar{b} \gamma_\mu \frac{\lambda_A}{2} b \right) - g_3 \tan \theta_t J_\mu^a \right] B^{\mu a} \quad (3.2)$$

where  $q_i$  are light quarks,  $\theta_t$  is the mixing angle between topgluons and ordinary gluons, and  $\cot \theta_t \gg 1$ . Because of the factor of  $\cot \theta_t$  in the first term and  $\tan \theta_t$  in the second, the process  $q\bar{q} \rightarrow \text{topgluon} \rightarrow b\bar{b}$  is independent of  $\theta_t$  (except where it enters through the topgluon width). This contrasts with  $b\bar{b}$  production through coloron exchange, which grows as  $\cot^4 \theta$ . Furthermore, heavy topgluons decay essentially only to  $t\bar{t}$  or  $b\bar{b}$ , while heavy colorons decay to all six quark flavors.

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<sup>2</sup>Axigluons [14] are the strongly coupled massive gauge bosons that remain in the spectrum after spontaneous breaking of an  $SU(3)_L \times SU(3)_R$  gauge group to the vector subgroup identified with QCD.

<sup>3</sup>Thus our limit on  $M_c$  with  $\cot \theta = 1$  agrees numerically with the limit CDF [13] gives for the axigluon mass.



In other words, (e.g. for topgluons and colorons heavier than  $2m_t$ )

$$\begin{aligned}\sigma_{topgluon} &\approx \sigma_{coloron}/\cot^4\theta \\ B_{topgluon \rightarrow b\bar{b}} &= 1/2 \\ B_{coloron \rightarrow b\bar{b}} &= 1/6\end{aligned}\tag{3.3}$$

which implies that  $(\sigma \cdot B)_{topgluon}$  and  $(\sigma \cdot B)_{coloron}$  are equal for equal-mass bosons when  $\cot^4\theta \approx 1.7$ . Using equation (1.5), this corresponds to  $\Gamma_c/M_c \approx 0.13$ .

CDF's range of excluded masses for narrow ( $\Gamma/M = 0.11$ ) topgluons of  $200 \text{ GeV} < M_{topgluon} < 500 \text{ GeV}$  therefore provides a rough idea of the limit for colorons with  $\cot^2\theta \approx 1.7$ . It appears that the limit on colorons from b-tagged dijets will be weaker than that from the full dijet sample. This contrasts with the case of topgluons, which can be more strongly constrained by the b-tagged dijet sample because they decay almost exclusively to third-generation quarks.

### 3.3 the $\rho$ parameter

An additional limit on the coloron mixing angle may be derived from constraints on the size of the weak-interaction  $\rho$ -parameter. Coloron exchange across virtual quark loops contributes to  $\Delta\rho$  through the isospin-splitting provided by the difference between the masses of the top and bottom quarks. Limits on this type of correction [18] imply that [1]

$$\frac{M_c}{\cot\theta} \gtrsim 450 \text{ GeV} .\tag{3.4}$$

This excludes the hatched region of the  $\cot^2\theta - M_c$  plane shown in figure 2. Note that this excludes an area of small  $M_c$  that the dijet limits did not probe, as well as an area at larger  $M_c$  and large  $\cot\theta$ .

### 3.4 critical value of $\cot\theta$

Finally, we mention a theoretical limit on the coloron parameter space. While the model assumes  $\cot\theta > 1$ , the value of  $\cot\theta$  cannot be arbitrarily large if the model is to be in the Higgs phase at low energies. Writing the relationship between the couplings  $\xi_1$  and  $\xi_2$  of the original gauge groups and the QCD coupling  $g_3$  as

$$\xi_1 \cos\theta = g_3 = \xi_2 \sin\theta\tag{3.5}$$

confirms that  $\xi_2$  is large when  $\cot\theta$  is large. If  $\cot\theta$  is large enough, then  $\xi_2$  exceeds its critical value, and the low-energy theory is in the confining phase rather than the Higgs phase.

Writing the low-energy interaction among quarks that results from coloron exchange as a four-fermion interaction

$$\mathcal{L}_{4f} = -\frac{g_3^2 \cot^2 \theta}{M_c^2} J_\mu^a J^{a\mu} \quad (3.6)$$

we use the NJL approximation to estimate the critical value of  $\cot^2 \theta$  as<sup>4</sup>

$$(\cot^2 \theta)_{crit} = \frac{2\pi}{3\alpha_s} \approx 17.5 \quad (3.7)$$

This puts an upper limit on the  $\cot^2 \theta$  axis of the coloron's parameter space, as indicated in figure 2.

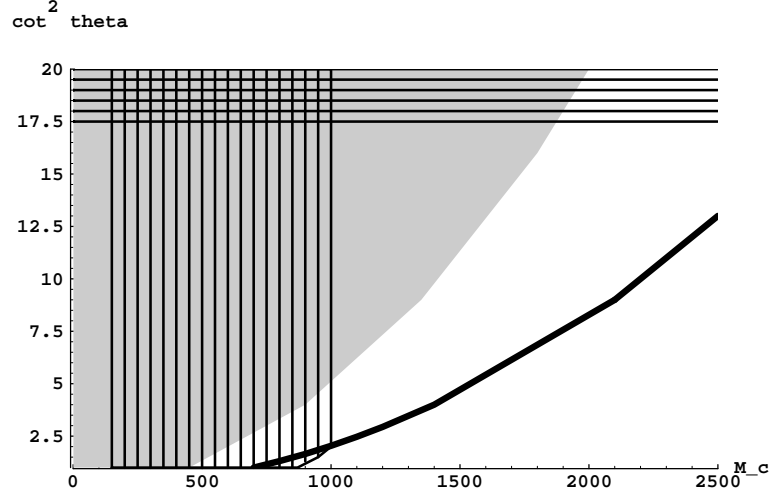


Figure 2: Current limits on the coloron parameter space: mass ( $M_c$ ) vs. mixing parameter ( $\cot^2 \theta$ ). The shaded region is excluded by the weak-interaction  $\rho$  parameter [1] as in equation 3.4. The vertically-hatched polygon is excluded by searches for new particles decaying to dijets [13, 16]. The horizontally-hatched region at large  $\cot^2 \theta$  lies outside the Higgs phase of the model. The dark line is the curve  $M_c / \cot \theta = 700$  GeV for reference.

## 4 Prospective limits

Data from run IA and IB at the Tevatron, from future Tevatron runs, and eventually from the LHC have the potential to shed further light on the flavor-universal coloron model. We suggest below what sort of analysis may prove useful.

<sup>4</sup>In more conventional notation (see e.g. [3]), one would write the coefficient of the four-fermion operator as  $-(4\pi\kappa/M^2)$  and find  $\kappa_{crit} = 2\pi/3$ .

## 4.1 jet spectra at the Tevatron

Both the inclusive jet spectrum ( $d\sigma/dE_T$ ) and the dijet invariant mass spectrum ( $d\sigma/dM_{jj}$ ) measured in CDF's run IA and IB data [2] appear to show excesses at high energy end of the spectrum. The dijet limits we derived earlier imply that the coloron is heavy enough that it would not be directly produced in the existing Tevatron data. Therefore, it is useful to start studying the data in terms of the four-fermion approximation (3.6) to coloron exchange. Comparison with the run IA CDF inclusive jet spectrum already [1] indicates that  $M_c/\cot\theta = 700$  GeV is not obviously ruled out, as figure 3 illustrates. Figure 2 indicates where the curve  $M_c/\cot\theta = 700$  GeV falls relative to the limits on the parameter space discussed earlier. Detailed analysis including both systematic and statistical errors should be able to determine a lower bound on  $M_c/\cot\theta$ .

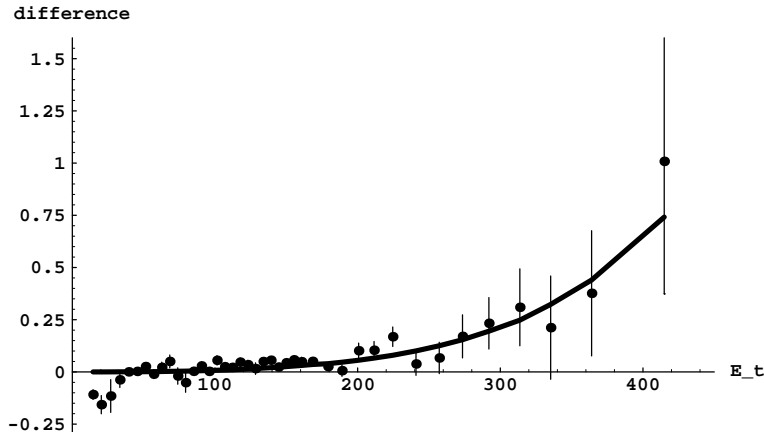


Figure 3: Difference plot  $((\text{data} - \text{theory})/\text{theory})$  for the inclusive jet cross-section  $\frac{1}{\Delta\eta} \int (d^2\sigma/d\eta dE_T) d\eta$  as a function of transverse jet energy  $E_t$ , where the pseudorapidity  $\eta$  of the jet falls in the range  $0.1 \leq |\eta| \leq 0.7$ . Dots with (statistical) error bars are the recently published CDF data [2]. The solid curve shows the LO prediction of QCD plus the contact interaction approximation to coloron exchange of equation (3.6) with  $M_c/\cot\theta = 700$  GeV. Following CDF, we employed the MRSD0' structure functions [19] and normalized the curves to the data in the region where the effect of the contact interactions is small (here this region is  $45 < E_T < 95$  GeV).

For colorons weighing a little more than a TeV – those that are just above the current dijet mass bound – it is more appropriate to use the cross-sections for full coloron exchange (see section 2) when making comparisons with the data. Such

colorons are light enough that their inclusion yields a cross-section of noticeably different shape than the four-fermion approximation would give (see figure 4). Once the full coloron-exchange cross-sections are employed, the mass and mixing angle of the coloron may be varied independently. In particular, one may study the effects of light colorons with small values of  $\cot^2 \theta$ . This can expand the range of accessible parameter space beyond what one would have reached by using the four-fermion approximation.

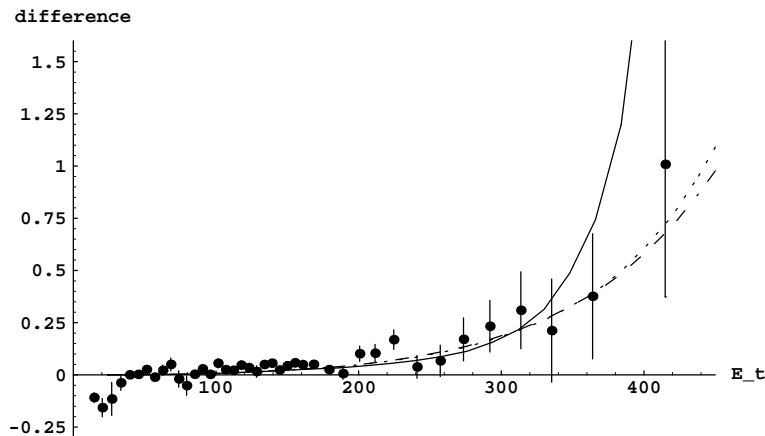


Figure 4: Difference plot for  $d\sigma/dE_T$  (see figure 3) showing the effects of colorons of different masses when the ratio  $M_c/\cot \theta$  is fixed at 700 GeV. Here full one-coloron exchange is included, rather than the contact interaction approximation. The solid curve is for a light coloron:  $M_c = 1050$  GeV,  $\cot \theta = 1.5$ . The dotted and dashed curves correspond to much heavier colorons ( $M_c = 1750$  GeV and 2000 GeV) with correspondingly larger values of  $\cot \theta$  (2.5 and 3.0). The cross-section for the heavier colorons is well-approximated by the contact interaction approximation at Tevatron energies; the cross-section for the lighter coloron is not.

## 4.2 dijet angular distributions at the Tevatron

Another means of determining what kind of new strong interaction is being detected is measurement of the dijet angular distribution. Some new interactions would produce dijet angular distributions like that of QCD; others predict distributions of different shape. In terms of the angular variable  $\chi$

$$\chi = \frac{1 + |\cos \theta^*|}{1 - |\cos \theta^*|} \quad (4.1)$$

QCD-like jet distributions appear rather flat while those which are more isotropic in  $\cos\theta^*$  peak at low  $\chi$  (recall that  $\theta^*$  is the angle between the proton and jet directions). The ratio  $R_\chi$

$$R_\chi \equiv \frac{N_{events, 1.0 < \chi < 2.5}}{N_{events, 2.5 < \chi < 5.0}} \quad (4.2)$$

then captures the shape of the distribution for a given sample of events, e.g. at a particular dijet invariant mass.

The CDF Collaboration has made a preliminary analysis of the dijet angular information in terms of  $R_\chi$  at several values of dijet invariant mass [10]. The preliminary data appears to be consistent either with QCD or with QCD plus a color-octet four-fermion interaction like (3.6) for  $M_c/\cot\theta = 700$  GeV. Our calculation of  $R_\chi$  including a propagating coloron gives results consistent with these. It appears that the measured angular distribution can allow the presence of a coloron and can help put a lower bound on  $M_c/\cot\theta$ .

### 4.3 heavy colorons at the LHC

Measurement of the inclusive jet and dijet spectra at the LHC will probe higher values of the coloron mass. The existence of a critical value of the mixing angle discussed earlier has an interesting implication for LHC experiments. Suppose analysis of Tevatron inclusive jet and dijet data finds that the best fit comes from including a four-fermion interaction of the form (3.6) with  $M_c/\cot\theta = X$  GeV. This four-fermion interaction can self-consistently be described as the low-energy manifestation of exchange of a massive coloron only if  $M_c \leq X \cdot \cot\theta_{crit}$ . Thus the Higgs-phase coloron model would predict that experiments at the LHC should find a coloron resonance at or below that mass. For example, figure 3 shows how a four-fermion interaction with  $X = 700$  GeV compares with the CDF inclusive jet data; that would correspond to a coloron weighing no more than about 3 TeV.

## 5 Conclusions

The flavor-universal coloron model can accommodate an excess at the high- $E_t$  end of the inclusive jet spectrum at Tevatron energies without contradicting other data. Previous measurements of the weak-interaction  $\rho$  parameter and searches for new particles decaying to dijets imply that the coloron must have a mass of at least 870 GeV. Ongoing and future experiments at hadron colliders have the power to test the model further. In particular, if Tevatron experiments identify a preferred value of

the ratio  $M_c/\cot\theta$ , then the upper limit on  $\cot\theta$  in the model's Higgs phase would yield an upper limit on the coloron mass to guide searches at the LHC.

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